Two-laser heterodyne metrology
for a separated spacecraft interferometer

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ABSTRACT

The proposed New Millennium Interferometer consists of three spacecraft separated by up to several kilometers. A heterodyne laser metrology system is proposed to measure the relative distances between the spacecraft. Because diffraction losses for a round-trip measurement are prohibitively large, a two-laser metrology system has been suggested in which each spacecraft has both a laser and a receiver, The system has been successfully demonstrated with a one Tinter baseline and verified by a conventional single-laser system in a laboratory experiment. The precision was limited by thermal effects in the room environment for time scales greater than one minute. The single-laser system obtained a precision of 3 nm for integration times up to 0.5 seconds. The two-laser system obtained a precision of 20 and was limited by self-interference and electronics noise. The resolution of the two-laser metrology system was $\lambda/30$.

key words: heterodyne interferometry, metrology, spaceborne interferometer

1. INTRODUCTION

A separated spacecraft interferometer (SS1) has been proposed as a New Millennium project whose objective is ultra-high resolution imaging[1]. Several spacecraft with large mirrors would collect star light and direct it to a central beam-combining spacecraft as shown in Figure1. The spacecraft are separated by 100 m to 10 km, providing angular resolutions from 1 milliarcsecond to 10 microarcseconds[2]. Because the spacecraft positions constantly drift, the baseline distances must be continually measured. A laser metrology system is proposed to measure the baselines

Diffraction losses limit the operating range of laser metrology system. For a system using a round-trip measurement, the fraction of light collected is $-(d/\sqrt{\lambda L})^8$. The proposed infrared laser at 1,3 pm with an optics diameter of 2.5 cm propagating over the maximum round-trip baseline distance 20 km diverges so that only 3x10-7 of the transmitted light is collected, Such a system requires either a detector with a sensitivity greater than the state of the art or an impractically large laser power. An alternative method uses two lasers, each of which makes a single pass along the baseline. The fraction of the light collected for a single, long-distance pass is $\sim (d/\sqrt{\lambda L})^4$, which for the above design parameters collects 6×10^{-4} and is within the capabilities for current sensors and lasers[4].
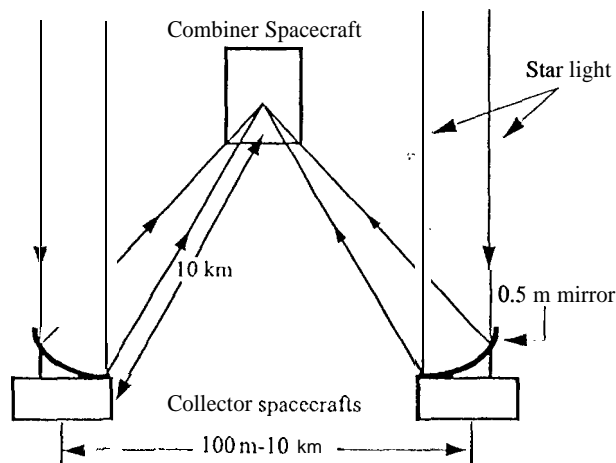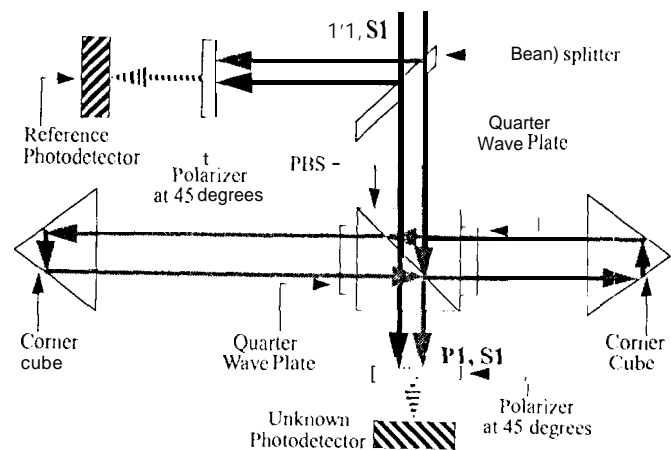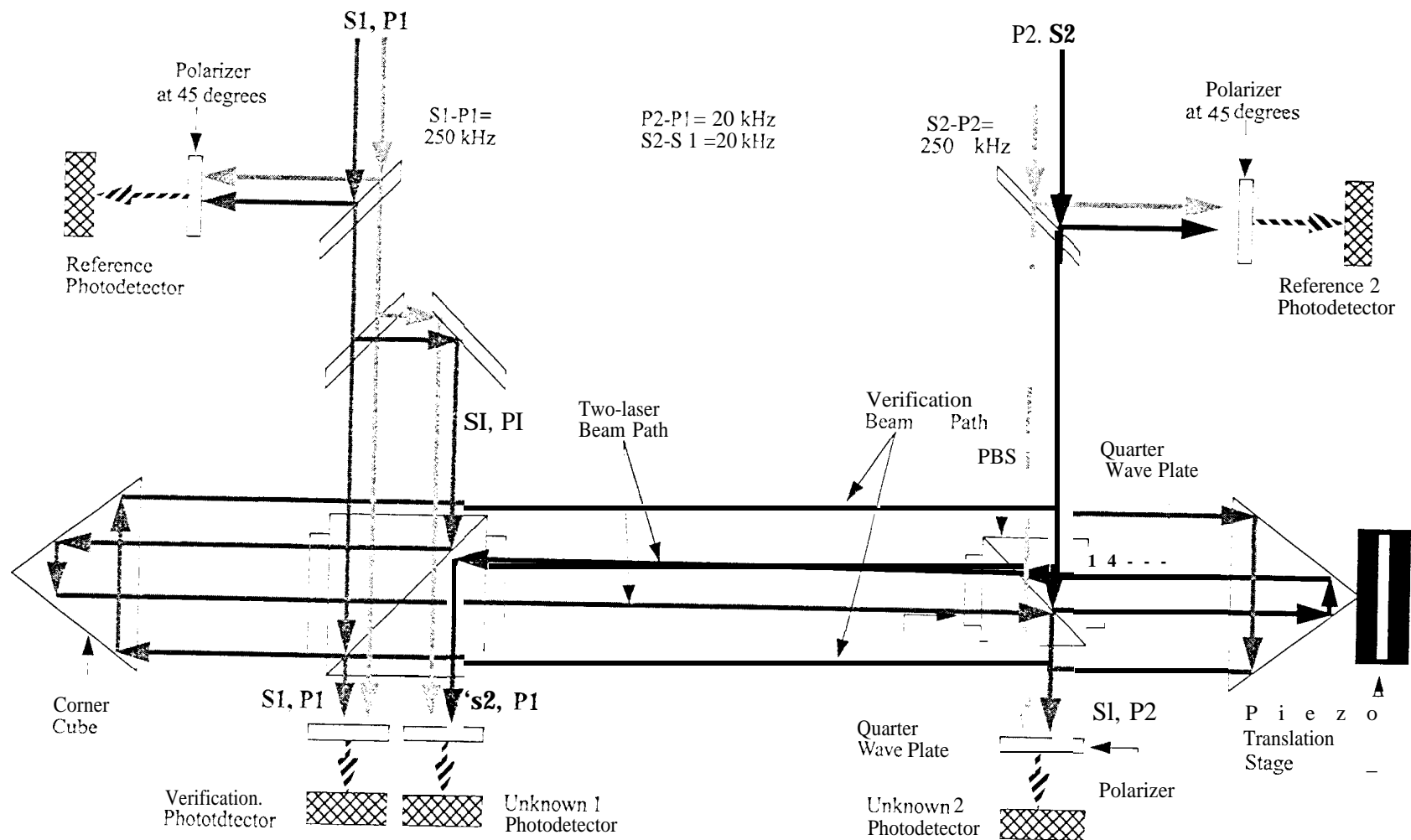
Figure 1. Separated Spacecraft Interferometer

Figure 2. Round-trip metrology beam path

The two-laser metrology scheme is a modification of the round-trip, heterodyne metrology systems developed at JPL[5,6] and discussed by Sirohi[7]. The concept of the round-trip system is illustrated in Figure 2 and summarized here. The round-trip metrology method uses two orthogonal polarizations (S and P), which are frequency shifted apart by a few MHz, to measure the distance between two corner cubes. The P polarization at frequency f] is the reference beam of the metrology interferometer, while the S polarization at frequency f2 is the measuring beam. The S beam travels the round trip distance between the two corner cubes and then is interfered with the reference beam.]n an ordinary interferometer, the optical path difference between the reference and measuring beams is the phase difference between the S and P beams. In heterodyning, the S and P beams, modulated at different arc interfered to produce a signal that beats at a frequency of f2 - f]. The signals also beat at f2 + f], but this higher frequency beat is not in detector range. The first detector (reference signal) with a reference phase φ_r monitors any path length changes between the P and S beams that occur before the beamsplitter. The second detector (unknown signal) measures a different phase φ_u. Subtracting the two detector signals gives the difference between the reference and unknown phase, $\varphi = \varphi_u - \varphi_r$, which monitors the distance between the two corner cubes. The phase φ is the round trip distance times the laser wavenumber so that $\varphi = 2kL/\lambda$ (modulo one wavelength). Change in φ, the phase difference between the two detector signals, is an instantaneous measurement of the change in the optical path difference between the corner cubes,

In the two-laser metrology system for the separated spacecraft interferometer, each spacecraft would have a pair of heterodyned S and P polarized laser beams, 'l'he S and P beams are interfered to produce the reference detector signals. The P beam remains on its spacecraft while the S beam is transmitted to the other spacecraft, making a single pass along the baseline, and is interfered with the P beam on the receiving spacecraft. As illustrated in Figure 3, S1 and P1 form a reference signal for one spacecraft while S2 and P2 form a reference signal for the other spacecraft, The measurement signals arc produced by S1 interfering with P2 and S2 interfering with P1, As shown below, these four signals (S1 - P1, S2-P2, S1-P2, S2-P2) arc required to determine the relative distance of the spacecraft.

The remainder of the paper describes the experimental implementation of the two-laser metrology system. The signal processing using the four detectors is discussed. The successful measurement of the motion of a corner cube is shown for ambient and oscillating systems. The resolution and error sources arc also discussed.

Figure 3. Two-1aser metrology interferometer with verification metrology interferometer

S1, P1

P2. S2

Polarizer at 45 degrees

S1-P1= 250 kHz

P2-P1 = 20 kHz
S2-S 1 =20 kHz

S2-P2= 250 kHz

Polarizer at 45 degrees

Reference Photodetector

Reference 2 Photodetector

SI, PI

Two-laser Beam Path

Verification Beam Path

PBS

Quarter Wave Plate

Corner Cube

S1, P1

's2, P1

Verification. Phototdtector

Unknown 1 Photodetector

Quarter Wave Plate

Sl, P2

Unknown 2 Photodetector

Polarizer

Piezo Translation Stage

1 4 - - -

2. EXPERIMENTAL SETUP

The two-laser metrology experiment is setup in three stages, The first stage splits the laser into the appropriate two pairs of polarizations and then modulates the polarized beams. The second stage is the two-laser metrology system and a separate verification interferometer (shown in Figure 2) to monitor the distance between the corner cubes. The third stage includes the signal processing which converts the heterodyne signals from the detectors into fractional fringe counts and processes the results on a computer.

2.1 Modulation Stage

The 1 mW helium-neon laser used was linearly polarized and had a frequency stability of 5 MHz in order to allow sufficient coherence length. The laser was split in to two beams, one to represent the laser at each spacecraft, each of which was split into orthogonal polarizations.

The beams were modulated with Bragg acousto-optic modulators which frequency upshift the deflected first order by an input RF frequency. Standard, crystal-driven synthesizer, CB radios provided the four RF signals. The orthogonal pair, S2P2, was upshifted 20 kHz from the other pair, S 1P1, and each S polarized beam was upshifted 250 kHz from its paired P polarization, as shown in Table 1.

beam	frequency	shift from P 1
P1	26.965 MHz	0 kHz
S1	27.215 MHz	250 kHz
P2	26.985 MHz	20 kHz
S2	**27.235** MHz	270 kHz

Table 1. Frequency modulations of the beams

The 20 kHz shift between orthogonal pairs represents the difference in frequency between the lasers on the two spacecraft. Some frequency drift on the order of a few kilohertz was expected from the different CB radios thus simulating the drift in frequency expected from the lasers on each spacecraft. Because each sampling of the detector signals registers the instantaneous frequency differences, the 20 kHz upshift and the CB drifts sufficiently demonstrate that a metrology system using two lasers at slightly different frequencies is feasible.

After modulation, each beam is coupled into a polarization-maintaining optical fiber for delivery to the metrology s yst em. Orthogonal pairs were not coupled into the same fiber in order to prevent polarization leakage and the resulting sc]f-interference.

2,2 Metrology Stage

The light exiting the fibers was collimated to 5 millimeter diameter beams and recombined into respective pairs, S 1 P 1 and S2P2, via polarizing beam splitters. A beam splitter in each pair directed a fraction of the light to the respective reference detectors.

The orthogonal pairs continue to their respective metrology launchers. The metrology launcher consists of a polarizing beam splitter with quarter wave plates on opposing sides. The polarizing beam splitter (PBS) passes the P1 polarization (modulated at f1) straight through. The beam, S 1, modulated at frequency f2 enters the PBS as S polarized and reflects to the corner cube. The beam passes through the quarter wave plate and becomes right-circularly polarized, Reflecting off the corner cube, the beam

becomes lef[-circularly polarized. incident on the quarter wave plate, the beam becomes linearly polarized in the P direction and transmits through the polarizing beam splitter. Passing through the second quarter wave plate, the beam becomes right-circularly polarized. The beam continues its single pass to the receiving beamsplitter. Incident on the quatcr-wave plate, the beam becomes linearly polarized in the S direction and is reflected by the PBS to the detector where it is combined with 1'2 after passing through a polarizers at 45 degrees. The S2 and 1'2 beams in the other half of the metrology system follow a symmetric path. The signals at each detector arc listed:

reference detectors:	P1-S1	(1)
	P2-S2	(2)
unknown detectors:	P2-S 1 +2k(l_2+$2l_1$)	(3)
	P1-S2+2k(l_2+$2l_3$)	(4)

Adding the two unknown detector signals, equations (3) and (4), and subtracting the two reference signals, equations (1) and (2), leaves a constant times the length, viz $4kl = l-_1+l_2+l_3$. In this manner the relative motion of the two corner cubes was obtained.

in order to verify the results from the two-laser metrology system, a second metrology interferometer was added which is a single-laser, round-trip heterodyne interferometer. This second metrology system, hereafter denoted the verification metrology system, has already been demonstrated at JPL.[8]. The 'verification metrology system shared a large PBS with the two laser metrology system, but avoided the second, smaller PBS to complete a round-trip beam path.

One of the corner cubes was mounted on a translation stage driven by a picz,o-electric actuator. The actuator expansion was measured using a round-trip metrology system to be 0.5 μm for each additional volt applied to the amplifier. The piezo-electric translation stage allows the distance being measured to be varied by as little as a tenth of a micrometer up to fifty micrometers. This motion of the corner cube on the translation state simulates the relative motion between spacecraft.

2.3 Electronics and Signal Processing

The final hardware component of the experiment is the electronics for the photodetectors. To accurately find the signal differences, the signals were digitized and processed on a VME-based computer board developed by JPL.[9]. On the board, the five detector sinusoidal signals (two reference, two test unknown, one verification unknown) were converted into square waves using zero-crossing thresholds, From the leading edge of the reference signal, the board counted increments to the leading edge of the unknown signal anti stored the counts in registers, where one wavelength was 256 counts. Taking a set of data involved initializing the counters, reading the counters synchronously at a rate of 100 Hz, and writing the counts to a file. From the file, the counts for each channel were processed to find the change in distance between the corner cubes.

3. RESULTS

3.1 Initial Results

As an initial test, both metrology systems accumulated data for fifteen seconds while the PZT stage remained static. Figure 4 demonstrates that round-trip, verification metrology system and the tvm-laser metrology system match.
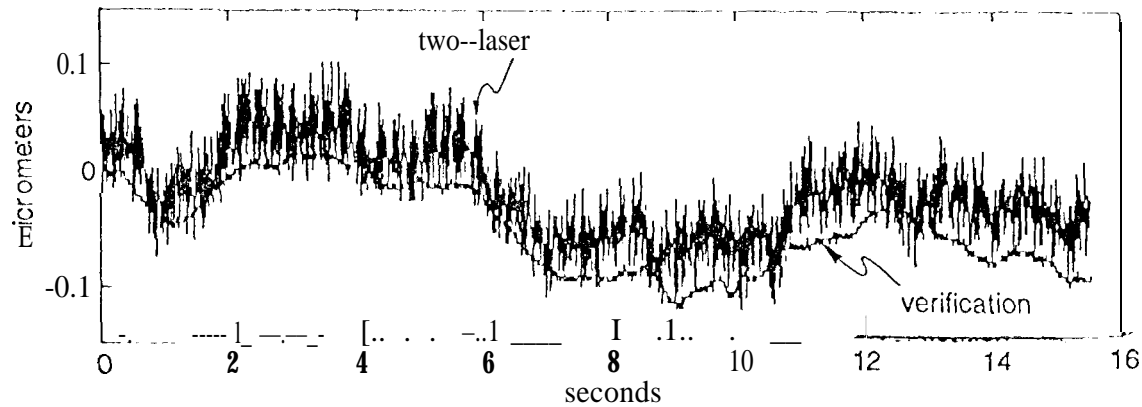
Figure 4. Fifteen second ambient data set.

3.2 Oscillation Results

The piezoelectric actuator moved one corner cube to demonstrate that a known change in distance was accurately measured. The PZT actuator was driven with a sinusoid at 0.1 Hz, 1 Hz, and 10117. Again, the two-laser system measurements were verified by the single metrology system. The two signals agree with each other within the noise expected from the two-laser system. Figure 5 shows the 0.1 Hz data and the difference between the two-laser and verification measurements.
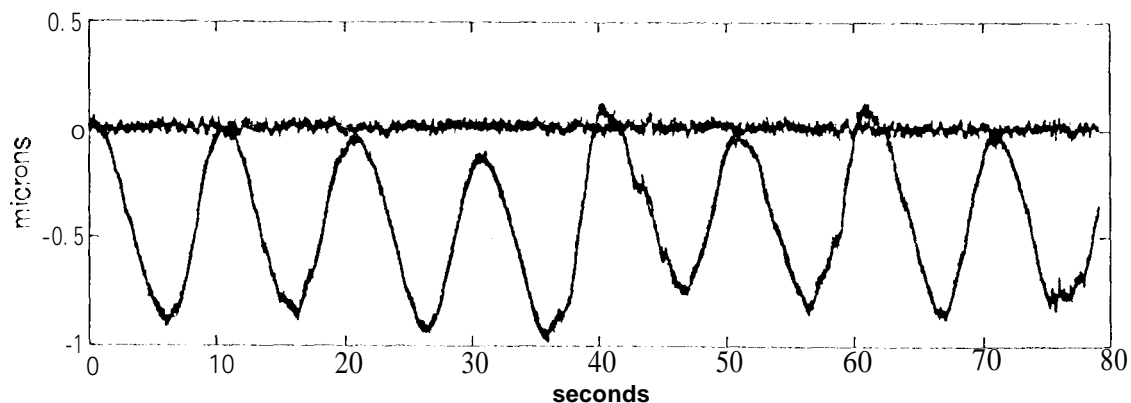

Figure 5. PZT stage oscillating sinusoidally at 0.1 Hz.

3.3 Ambient Results

Some amount of motion is expected in a "ambient system", which means no driving signal is applied to the PZT stage. Any motion in the system is caused by slow, small scale motion of the optical components and air currents. A gas flowing through a coherent light beam disturbs the phase of the wavefront. If the gas has an index of refraction with a temperature dependence of $5 \times 10^{-7}/C$-m such as air, a 1/10 degree Celsius temperature variance would produce a 100 nm change over one meter of length. The optical path length between the corner cubes is about one meter, so a variation of 100 nm in the data is not unreasonable for 5 minute times scales,

Four data sets, each five minutes long, were taken for an ambient system on different days. The standard deviations of the four data sets were 162 nm, 97 nm, 103 nm, and 138 nm for both the verification and the two-laser measurements. This indicates that the noise in the measurement is limited

by thermal effects on time scales of several minutes. On the shorter time scale of half a second, the standard deviation of the verification measurement was 3 ± 1 nm, while the standard deviation of the two-laser measurements was 18 ± 5 nm. Both systems are limited by self-interference which is greater in the Iwo-laser system.

3.4 Self-Interference and Noise

Self-interference occurs in the single metrology system when polarizations leak through the polarizing beam splitter. The polarizing beam splitter reflects only 99% of the S polarization and less than 2% of the P polarization while it transmits 98°A of the P polarization less than 1 % of the S polarization. Consequently, the optical signals on the detector consist of four signals: the desired S and P signals and the two leakage S and P signals. For the verification metrology system, this self-interference was minimized through optical alignment to be about So/O of the signal. The leakage signals also beat at 20 kHz and create a systematic error with the period of one wavelength. This error can be removed through cyclic averaging[8].

The additional frequencies of the two-laser system prevent cyclic averaging. Consider the second unknown detector: the desired signal S 1 beats with P2 at 270 kHz, while S2 beats with P2 at 250 kHz, and S 1 beats with S2 at 20 kHz. The self-interference was 14% and 11 % of the desired signal on the two unknown detectors. The self-interference adds jitter to the zero crossing of the desired signal, producing noise in the digitized signal. The 5% self-interference of the verification system should result in about 4 nm of noise, which is observed. The 14% and 11 % noise in the two detectors of the Iwo-laser system add in a root squared manner to predict 18 nm of noise in the measurement, which is observed. On time scales of several seconds, the experiment is limited by self-interference. Self-interference may be reduced by minimizing polarization leakage using a half wave plate to rotate the S and P polarizations to precisely match the axis of the polarizing beam splitter.

4. CONCLJSIONS

The experiment shows that the two-laser metrology system successfully measures the change in distance between two corner cubes. The measurements made by the two-laser metrology system were verified by the single-laser, round-trip metrology system. The difference between the two metrology systems was dominated by the noise of the two-laser metrology system. The noise on the two-laser system detectors was largely due to self-interference and could be improved using optics to more precisely align the rotation of the polarized beams. The noise per 0.01 second sample integrated up to 0.5 seconds was 3 nm for the verification system and 20 nm for the two-laser metrology system, This yields a resolution of $\lambda/30$ which meets the objective of this experiment.

For a static metrology path, the standard deviation of the measurement integrated over 5 minutes was 100 nm for both the two-laser and single-laser systems. Air currents and mechanical drifts cause the 100 nm deviation. This deviation could be reduced by placing the metrology stage of the experiment in a vacuum chamber.

oscillating one of the corner cubes demonstrated that the two-laser metrology system measurements were verified by the single-laser metrology system within the per sample noise measured in the static tests and that the two-laser metrology system can measure the changing distance between corner cubes. This confirms that a metrology system between separated spacecraft, each carrying its own laser, is possible.

5. ACKNOWLEDGMENTS

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